

Telecommunications Tools Applications and Analysis Service for DS1 Mission

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Abstract—In the “faster, better, cheaper” era, the Jet Propulsion Laboratory (JPL) continues to develop smaller and more frequent missions. The Deep Space Network (DSN) must track many spacecraft simultaneously. With ground tracking resources limited and with NASA’s moving into an era of full cost accounting, the need for an efficient and well-coordinated multi-mission telecommunications analysis service is apparent. This service is now provided as part of Telecommunications and Mission Operations Directorate (TMOD)’s Deep Space Mission System (DSMS). DS1 is the first mission to subscribe to TMOD’s services. This paper describes the DS1 telecommunications link analysis service scenarios, including the DS1 safing incident on July 28, 1999, the day of Asteroid Braille flyby. The theme of this paper is to demonstrate that good people, efficient processes, and effective tools are key elements that enable 1) a wide range of cost-effective telecommunications analysis support, and 2) timely detection and anticipation of unforeseen situations.^{1,2}

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1. INTRODUCTION

The Jet Propulsion Laboratory (JPL) continues to develop and fly smaller spacecraft in more frequent missions in this “faster, better, cheaper” era. Consequently the Deep Space

Network (DSN) must track more spacecraft simultaneously. Project flight teams are also smaller. With ground tracking resources limited and NASA moving into an era of full cost accounting, it is a luxury for each flight mission to fund telecom analysts individually. The need for efficient and well-coordinated telecommunications analysis among many projects and the DSN is apparent. The Telecommunications and Mission Operations Directorate (TMOD) of JPL meets this need by providing a Telecom Analysis Service as one part of its Deep Space Mission System (DSMS). Deep Space 1 (DS1) is the first project managed by JPL to subscribe to some TMOD services. This paper describes the meshing of a TMOD telecom analyst into the project pre-launch development and the subsequent telecom analysis activities in flight. During the nine months leading up to DS1 flyby of the asteroid Braille on July 28, 1999, both TMOD and project-funded telecom analysis played a significant role in day-to-day mission planning, sequence development, data monitoring and interpretation, technology validation (“tech val”) activities and anomaly identification and resolution when needed. The theme of this paper is to demonstrate that good people, efficient processes, and effective tools are key elements that enable 1) a wide range of cost-effective telecom analysis support, and 2) timely detection and anticipation of unforeseen situations.

The broad challenge given to TMOD telecom analysis by DS1 was: “Tell us how to command our spacecraft.” This challenge becomes more specific in terms of the three components of telecom analysis: prediction of link performance, comparison of reported link performance against predictions, and telecom model or parameter update that leads to subsequent prediction. Telecom analysis service can also be generally classified into 1) pre-launch planning and development, and 2) in-flight prediction, comparison, and planning. Pre-launch activities for DS1 included a telecom tools adaptation effort, the planning of telecom’s role in flight operations, and estimation of uplink and downlink data rate capability based on published station capabilities and ground testing of the spacecraft. Post-launch support has been provided to DS1 with a combination of expertise, processes, and tools. The in-flight telecom analysis includes sequence planning and pre-pass link prediction, post-pass trend analysis and coordination of

¹ This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

² 0-7803-5846-5/00/\$10.00 © 2000 IEEE

corrective action, and spacecraft anomaly identification and resolution.

Telecom analysis for flight operations has become much more software intensive in the 1990s. Telecom analysis for DS1 made use of four major tools.

Telecommunications Forecaster Predictor (TFP). Adapted to include DS1 spacecraft models, the TFP is a multi-mission tool for communication link prediction [1]. It is built upon the commercial software Matlab, a technical computing environment for high-performance numeric computation and visualization. The TFP has a graphical user interface (GUI) to allow the analyst to enter inputs and select link configuration and parameters. The TFP allows users to generate a wide variety of plots and tables for display, hardcopy, or file input to a spreadsheet.

Unified Telecommunications Predictor (UTP). The UTP is the batch mode counterpart of the TFP that generates telecommunications predicts to configure and operate the Deep Space Communications Complex (DSCC) telemetry subsystem. For DS1 and future missions, UTP has been adapted to generate data rate capabilities as a file (the DRCF) to facilitate mission planning and sequence generation. Figure 1 is a sample of one form of a DS1 DRCF. The UTP uses the same models as TFP for tracking stations and the spacecraft to compute prediction values of link performance for a specific flight project.

Service Package Writer (SPW). New for DS1, the SPW uses pre-defined link configuration templates to generate both service packages (an input to project sequence generation process and DSCC's Network Planning and Preparation Subsystem) and UTP mode files (an input to UTP). Figure 2 is a sample DS1 service package.

Derived Channel Processor (DCP). Also built upon Matlab, the DCP provide capabilities to compare actual link performance to predicted performance. DCP accepts input files from a standard multi-mission JPL software tool, TelRet (Telemetry Retriever).³ Adaptation of DCP for DS1, which occurred after launch, consisted of minor updates for data channel numbers. Figure 3 is a sample DS1 TelRet/DCP link performance comparison plot.

The rest of this paper is organized as follows. Following this introductory Section 1, Section 2 briefly describes the statistical nature of telecommunications link design, as incorporated into the TFP models. Section 3 discusses the key attributes and standard components of the multi-mission telecommunications analysis service. Section 4 describes the adaptation of the standard service and the specific

application of its processes through the DS1 project lifecycle. Section 5 provides a detailed account of the role of telecom analysis in the DS1 safing incident on July 28, 1999, the day of the spacecraft flyby of the asteroid Braille. Section 6 documents the lessons learned from our experience through the several phases of telecom analysis support for DS1. Section 7 gives our conclusions about the degree of success of DS1 use of TMOD telecom analysis service.

2. STATISTICAL APPROACH FOR TELECOMMUNICATIONS LINK ANALYSIS

A typical spacecraft communications system performs three basic functions: telemetry, command, and tracking. The telecommunications link encompasses the entire communications path, from the information source, through all the encoding and modulation steps, through the transmitter and the channel, through the signal processing steps in the receiver, and terminating at the information sink. Most link parameters are neither constant nor precisely known. The communication channel, which is the propagation medium connecting the transmitter and receiver, introduces random noise that is unpredictable except in a statistical sense. Some link parameters vary with spacecraft environment, others with ground station configuration and the communications channel conditions. Some are associated with link components that have manufacturing tolerances.

Through the experience of many deep-space missions, telecom system designers found they could not state link performance by simply assigning conservative values to each link parameter. It was found that actual link performance was almost always several dB better than that predicted by combining of adverse values. A better tool for modeling the performance of a system with many parameters (which are modeled as independent random variables) was needed, to avoid over-designing the telecom system or under-predicting the data rate (and hence the achievable science data return).

Telecommunications link analysis is a statistical estimation technique for evaluating communications system performance. It calculates and tabulates the gain and loss parameters in terms of statistical link. A detailed discussion of this technique is given in [2]. This technique, which has been standard at JPL since 1970, is used in the prediction of both pre- and post-launch telecommunications performance for all JPL deep-space missions, including DS1.

³ TelRet (Telemetry Retriever) is one of the software utilities provided to the DS1 project by the MSAS (Multimission Spacecraft Analysis Subsystem) software development team. DCP stands for the Derived Channel Processor. TelRet queries station data, DCP allows the telecom analyst to compare telecom predicts produced by TFP with actual station data.

3. TELECOMMUNICATIONS ANALYSIS SERVICE

Telecommunications link analysis service provides the means (which may include tools and their adaptation, and the people to use the tools and interpret the output) for a flight project to plan the communications configurations, capabilities, and operation strategies between a spacecraft and the tracking stations of the Deep Space Network. This service also assesses the resulting tracking performance against the plans.

The kind and extent of telecommunications analysis that a mission needs varies from mission to mission, and also is different for each phase of a mission. The challenge of a multi-mission telecommunications analysis service is to develop the right combination of expertise, processes, and tools to meet a wide range of customers' needs, which may be

1. minimal due to simple mission operations and/or large link margins,
2. occasional due to infrequent tracking,
3. significant due to mission critical events,
4. detailed due to complicated mission operations and/or low link margins,
5. intensive due to telecom involvement in anomaly resolution.

In an 18-month pre-launch development, an 11-month prime mission flight, and a planned 2-year extended mission, the DS1 project's telecom analysis needs have varied with mission phase, and have ranged from level 2 to level 5.

The effectiveness and timeliness of the service depends strongly on the software tools. A detailed description of the Telecommunications Forecaster Predictor (TFP) tool is given in [2].

The standard telecommunications link analysis services are:

Prediction tool configuration - Incorporate mission- and spacecraft-specific parameters into the database of the standard TMOD telecom prediction tool. Verify the applicability of standard communication link and station models and auxiliary data interfaces to the project requirements. Standard interfaces with ephemerides, station viewperiods, spacecraft pointing, and station scheduling data are available.

Long-range prediction generation - Provide long-range uplink and downlink data rate capability predictions for project planning.

Analysis environment setup - Provide data displays, data analysis tools, documentation and training, and access to spacecraft telemetry and station monitor data for telecom link performance analysis.

Telecom link documentation - Provide or generate spacecraft and station parameters and description. The parameters are those required to complete a Design Control Table (DCT) for each required uplink and each downlink mode and frequency band. The DCT, also called a link budget, is used to validate a new or updated model as well as to predict link performance for one configuration at one point in time. A DCT assumes a fixed geometry, such as range, station elevation angle, antenna gain, etc. Tabulations or plots describing the variation of specific link parameters with time can augment the DCT.

Service package preparation - Starting with uplink and downlink capability predictions and a statement of project telecom activities, prepare a set of service packages for the next mission phase. Services are provided by the Deep Space Station and include such functions as Doppler, telemetry, command radiation, and ranging. A service package contains a set of spacecraft and station parameters and their values that enables the station to provide that service to the project.⁴

Real-time monitoring - Observe, assess, and report on-line to project personnel the spacecraft telecom subsystem telemetry and the station performance data during station passes.

Post-pass analysis - Acquire and analyze (compare against the predictions) the spacecraft telemetry and station monitor data for RF signal power, system noise temperature, telemetry and ranging channel signal-to-noise ratios, and telemetry data frame decoding corrections. Store the analysis results in the project database.

Trend Analysis - Analyze and provide reports on telecom performance trends, including recommendations to avert impending problems with spacecraft or station equipment. DS1 telecom reports range from brief oral statements of onboard subsystem health at daily project meetings, to e-mail documentation of the station performance of one or more passes, to the formal technical validation ("tech val") reports at the end of the prime mission.

Flight Team Participation - Provide telecom analysis support to team planning and status meetings, reviews, and reports. Respond to telecom capability "what if?" (planning) and "why did it?" and "is this a serious problem?" (performance) questions.

⁴ The DS1 service package is a file used by the sequence engineer to generate both a spacecraft sequence of commands file and a DSN keywords file (DKF). The DS1/TMOD plan was for telecom analysis also to submit service packages to TMOD as a statement of the required start and end times for each service in each pass and the overrides to the mission service tables (which contain default parameter values for DSN services). The agreement changed such that the project sequencing process would generate from the service packages a DKF to submit to TMOD as a time-ordered list of station actions for the passes in the sequence.

4. DS1 TELECOM ANALYSIS PROCESS

This section does not present a perfect or fully mature process. Rather, it shows the functions and tasks that have been performed by telecom analysis for the Deep Space 1 (DS1) mission. This section describes how the telecom analysis people and tools worked together to meet various project needs. We believe the functions described below have to be performed on any typical deep space mission, so this will serve as a reference to users who are planning to do a mission.

A more detailed description of the DS1 telecom analysis process is given in an upcoming TDA Progress Report [3].

Pre-Launch Activities

Subsystem Testing and Parameter Documentation—The prime mission of DS1 was technology validation. Rather than the gathering of science data, the main emphasis of the mission was to demonstrate the performance of new technologies for use in future missions. New telecom technologies aboard DS1 included the Small Deep Space Transponder (SDST) and the Ka-band solid state power amplifier (KAPA). Telecom analysts, together with the hardware developers, planned and conducted in-flight tests of the SDST and KAPA, in which performance prediction was an important factor.

The pre-launch development of the DS1 Telecom system was done on a very tight schedule (1 1/2 years, versus 3 years for previous JPL missions). Tests were performed at Motorola (the SDST contractor), at JPL in different labs, and at the Cape and documented in electronic form. Performance characteristics such as the non-linearity of the X-band phase modulator were analyzed and modeled for use in link prediction software.

Project Requirements and Plans—About 1-1/2 years before launch, the DS1 project contracted with the Telecom and Mission Operations Directorate (TMOD) organization at JPL to be provided a Telecom Analysis service. TMOD initially assigned one telecom analyst who worked side-by-side with the project telecom designers to develop operational aspects of the system.

As the project developed its mission operations system (MOS) plans, the requirements on telecom analysis for flying the mission became more specific. At top level, telecom analysis consists of four activities: prediction of telecom link performance for planned sequences or known configurations, analysis of obtained performance against predicts, updating of telecom prediction models, and generation of new planned command sequences to continue the mission

Planned telecom characterization tests included five major areas:

Telemetry: the in-flight verification of 19 data rates (from 10 bps to 19908 bps) at both X-band and Ka-band

Modulation linearity: the interaction of telemetry and ranging modulation at both the low and the high ranging modulation index

Carrier frequency stability: the stability of the downlink carrier in both the two-way coherent mode frequency driven by the station's uplink and the one-way mode driven by an on-board oscillator, and

X-band compared with Ka-band: modulated and unmodulated X-band and Ka-band downlinks.

Characterization of the SDST receiver was accomplished through the routine uplink acquisition and tracking of the RF carrier, modulation of the carrier by ranging modulation, and the command activities that occurred with every pass.

Telecom Parameter/Model Development (Excel)—Early in the design process, the telecom analysts used a link performance spreadsheet produced by the Microsoft Excel program. A similar spreadsheet had been used successfully for analyzing many missions, including Cassini. The spreadsheet is a very versatile tool for developing new link models based on test data. DS1 examples include modeling the X-band phase modulator, which was highly nonlinear, and modeling ranging and command performance. We used the spreadsheet as well as for performing numerous design-phase "what if" performance trade studies.

Design Control Document (First Mission With a DCD "On the Web")—The pre-launch development team assembled all the relevant performance data and analyses into a Design Control Document (DCD) on the Internet⁵ for two reasons:

1. to transfer knowledge between the pre-launch and the operations team and
2. to provide an easy-to access reference for any telecom analyst on DS1.

(Traditionally, flight projects such as Cassini and Mars Global Surveyor have published and maintained the DCD as a paper book.)

Prediction Tool Development for Flight Operations—Development (adaptation) of TFP for DS1 began pre-launch but has continued well into the prime DS1 mission. Both phases are described here.

⁵ The DCD is available at the internal JPL URL <http://dsp.jpl.nasa.gov/~chen/>.

Pre-Launch: Setting Up TFP—Telecom analysts used an Excel spreadsheet program to evaluate link performance when developing the subsystem design and making performance trade-offs. But the very strengths of the Excel tool for development made it not well suited to the operations environment.

While a developer wants flexibility in use, in operations the analyst wants all the link calculations to be done using the same, validated model (so once the model is validated, one does not need to continually re-check the results). In other words, flight operations requires configuration control of the parameter values and models that are to be used.

For DS1, the telecom analysis development group recommended the Matlab-based Telecom Forecaster and Predictor (TFP), which was already used by Cassini and was being used to support several other missions (like Mars'98).

The correctness of the TFP models was verified extensively by comparing TFP outputs with Excel outputs. The Excel models and output values, already checked out, provided a benchmark for the TFP.

Post-Launch Activities

*Fine-Tuning TFP: Parameter Updates and "Addpath"*⁶ — The modeling and use of TFP was an iterative process due to changing mission needs. TFP was designed pre-launch with a 'baseline' set of capabilities. Planning in-flight activities, such as technology validation tests or spacecraft pointing maneuvers, revealed the need for more flexibility. Fortunately, the TFP developers gave us a very robust and flexible tool, so all these changing needs could be met.

TFP had one capability that became very valuable to the analyst, the "addpath." The addpath is a file directory containing the link models that an analyst wants to use. The models in the addpath supercede those of the standard, officially-delivered TFP version. We still used almost the entire set of well-tested models, but a needed set of TFP model changes or output format updates could be included in an addpath file directory without having to wait for another official release. The "addpath" is an example of good balance between configuration control and flexibility. It allowed the telecom analyst to provide quick turn-around support to the DS1 project's many "what if" questions.

Telecom Involvement in Spacecraft Sequence Development—Sequences of spacecraft commands are reviewed for consistency with flight rules, and to ensure that they accomplish the intended activities without harming the spacecraft. Generally sequence generation and review is iterative because of interaction between subsystems,

evolving mission needs, and results of ground testing of the sequences.

Approved sequence files and individual real time commands (some of which are used to activate or deactivate sequences stored on-board) are moved to the station for radiation by the project's real time mission controller. The mission controller is known by the on-net call sign "ACE". The ACE is the project's interface with the station and operates under direction of a Flight Director who has the signed command forms.

(Please refer to [3] for a more in-depth discussion of the sequence development process.)

Telecom Software Input/Output Fileflow—Generation of telecom configuration sets and signal level predictions does not take place in isolation. Operational predictions require the input of data files for spacecraft trajectory and antenna pointing. In turn, the predictions themselves are organized into files that follow a specified format.

A significant pre-launch development on DS1 was to plan on what sets of data were the responsibility of each group, when they would be created and updated, and the means by which they would be delivered and announced. The fileflow plan of trajectory and DS1/DSN file interfaces has been formally documented and is maintained by the project. The fileflow diagram shown in Figure 4 identifies the project teams, the TMOD services, the formally delivered files, and the expected frequency of file updates. Figure 4 is intended to convey an idea of the complexity of interfaces between different teams.

Testing of Analysis Software—A major telecom analysis challenge on DS1 has been to develop, learn to use, and debug several tools that required fine-tuning. It definitely was not a 'turn-key' environment! Though this process has made the DS1 telecom prediction software reliable and the link models mature, there's no such thing as a software tool that becomes bug-free and no longer requires any updating.

After launch, a second powerful way of checking the trajectory and telecom prediction software correctness became available, the direct comparison between a predicted quantity such as a signal-to-noise ratio and the value reported by the spacecraft or station receiving system. Errors in modeling spacecraft pointing and telecom parameters as well as typos in data tables were made evident by this kind of checking. The usual result of such checking, small residuals, showed that the models were done correctly.

*Procedures and Memory Aids for Standard and Repetitive Tasks*⁷—DS1 procedures are approved (maintained under

⁶ Refer to the TFP user's guide, a JPL publication, for a description of this feature.

⁷ The procedures used by the DS1 Flight Engineering Team are all documented and available through the internal JPL URL <http://eis.jpl.nasa.gov/~rbasilio/satv/mcdl.html>

configuration control) by a team chief. A telecom memory aid is a small or informal procedure not under configuration control. Use of procedures and memory aids created by the DS1 telecom analysis lead made the training of other analysts possible in a limited time environment. They also serve as checklists for an experienced analyst when there is no time to re-discover how to use a computer process used a month previously but not thought about until suddenly needed again. The procedures and memory aids show how improvements might be made to streamline a process. Ours was a workable system. It captured knowledge so that the lead analyst would not be the only one who knew what data was where and what to do with it.

In-Flight Planning of Telecom Capability (DRCF)—When predicting communications link performance, the analyst (with the aid of TFP) estimates the mean received total power-to noise spectral density (P_t/N_o), as well as a measure of the uncertainty of it (characterized by its standard deviation, σ).

Each flight project determines which level of risk, or uncertainty it will accept when predicting link performance. Typically, the statistical mean of P_t/N_o minus a multiple of the statistical standard deviation σ (e.g., two) is used when estimating the achievable command or telemetry data rate, and other functions such as Doppler and ranging.⁸

Performance predictions, based on P_t/N_o , are given in a Data Rate Capability File (DRCF) for uniformly spaced points in time and different link configurations. A link configuration includes the kind of tracking station, the kind of spacecraft antenna, simultaneous ranging channel usage or not, and spacecraft pointing assumption. The DRCF documents a profile of telecom link capability for each link configuration.

The mission planners are the primary users of the DS1 DRCF. The first use made of it is to judge the number of station passes per week and the type of tracking station that would be required during a particular mission phase to return the data that will be produced. Later, the telecom analyst uses the DRCF to specify the data rate commands to be placed in the sequence for each station pass. The analyst makes adjustments for special activities such as a technology validation that requires the HGA to be pointed a fixed number of degrees from earth at a specific interval during a scheduled station pass.

Pre-launch, we planned a DRCF format for 28 specific configurations, each one of them requiring a run of the program to cover the whole mission daily at a fixed station elevation angle of 10 deg. While these 28-run products have been useful for long-range planning, our in-flight experience showed a need also to be able to make

predictions for a smaller set of specific configurations over shorter periods of time and with smaller time increments with actual station elevation angles, corresponding to individual sequences. The software was updated accordingly, so that it could quickly generate a DRCF “intermediate file” for one specific link configuration. See Figure 1 for a sample DRCF intermediate file.

In-Flight Pass Predictions (TFP, “Just in Time”)—Station pass predictions are the second type used in daily operations. Pass predictions are needed by the ACE to brief the station as to expected carrier signal level and telemetry signal to noise ratio. They are also referred to by the ACE or the telecom analyst during real time data monitoring sessions to confirm the spacecraft and the station telecom equipment are properly configured and operating.

Real-Time Data Monitoring—DS1 has a Mission Support Area (MSA) that provides the means for project analysts to see data and provide control of the spacecraft in a single location. The MSA has workstations for query, display, and processing of telemetry and station monitor data, as well as voice nets for communications among the analysts. Telecom analysis is one of about 15 positions in the MSA. During real time support, the flight team follows a procedure and sequence of events (SOE) for the activity.

A traditional science mission has a “quiet” early cruise period during which the flight team learns to fly the spacecraft, followed by a science period with intense activity. DS1 did the opposite because of its “technology validation” nature. Many in-flight tests were conducted during the first few months after launch, requiring extensive real time support.

Daily “Health & Safety” Monitoring and Reporting—It has been a telecom goal to review spacecraft telecom performance telemetry (currents, temperatures, RF power levels) using the project telemetry system to make a set of standard plots of the measurements vs. time. For station data, telecom uses the Deep Space Network’s real time multi-mission display system, the NOCC RT. This system provides tabular and graphical displays. NOCC RT data is organized by station, data type (tracking, telemetry, command, and monitor), spacecraft, and start time.

The “Telecom Book” (Record of Day-to-Day Data)—There are two major sources of data for telecom.

spacecraft telemetry, which is stored electronically. All spacecraft data since launch is available to members of the flight team.

DSN station performance data, called monitor data. It is much more voluminous, and is stored electronically for only for the most recent month.

Both kinds of data, as well as supporting material such as sequences and SOEs, have to be accessible for stored

⁸ This “mean minus two sigma” is given as an example; typically pre-launch, when there is more uncertainty (the hardware has not yet been built and tested), an analyst will use 3 dB as a performance margin, rather than 2 sigma.

sequences, in-flight tests, and planned or unplanned real time activities (such as recoveries from safing). Data comes in different forms (electronic and hardcopy), from different platforms at different rates.

To cope with the data variety and to maintain a permanent record, telecom adopted a paper-based system of loose-leaf notebooks with sections made for each tracking day.

Post-Pass and Performance Trend Analysis—DS1 repeated the good fortune of most previous flight projects in that the on-board telecom hardware and software was extremely stable in-flight. Its performance had been well characterized during subsystem testing and spacecraft-DSN compatibility testing. The availability of the pre-launch telecom development team was crucial in training the flight team telecom analysts in the meaning of the data and how to interpret it (what was nominal, what was not, why did this channel update or not, and so forth).

There have been no unexpected trends in performance telemetry of any of the on-board telecom hardware. In contrast, there have been unexpected variations in measured station monitor data. The prediction tool TFP and the analysis tools TelRet/DCP were used to compare reported values against predicted values for each station pass.

An example of the use of these tools together is shown in Figure 3. This figure is a plot of telemetry symbol SNR versus time for one station pass. The reported values ("actuals"), appearing as scattered points, were obtained through one tool, called the Telemetry Retriever (TelRet). The predicted values ("predicts"), appearing as a smooth curve, were generated with TFP. A third tool, DCP, first did time-synchronization of the actuals and predicts. Then, by plotting them together, DCP shows the analyst the link residual (the actual level minus the predict level).

Use of the post-pass and trend analysis results enabled telecom to quickly verify which spacecraft antenna was in use, whether that antenna was pointed as planned, and whether the telemetry mode corresponded to a normal or a "safemode" condition. The station might be able to lock up on a downlink carrier at the beginning of a track, but have difficulty with the telemetry subcarrier or symbols. Previous telecom assessment of the carrier level might result in a recommendation to the ACE to have the station change a receiver loop bandwidth or to look for a different subcarrier frequency. In another instance, a weaker than expected uplink received carrier power in the telemetry data suggested that the station antenna pointing model required update.

5. ASTEROID BRAILLE FLYBY AND SAFING SUPPORT

Telecom Planning for "Encounter Rehearsal"

Flyby of the asteroid Braille by DS1 occurred in the late evening of July 28, 1999. Several weeks before that, the DS1 spacecraft "rehearsed" the portion of the sequence from several hours before closest approach to several hours after. As nearly as possible the rehearsal sequence duplicated the commands and subsequences that were being developed for the real encounter. The rehearsal also validated the sequence generation and review, and provided some personnel training though the latter was not its purpose.

Telecom Planning for Encounter "Closest Approach Sequence"

The telecom involvement in encounter was similar in kind to previous sequences, though more complex. For some passes, 70-meter stations supported the downlink at a higher rate than the 34m stations would be able to. For the passes just before, during, and just after closest approach, dual support was provided by both 70m and 34m stations, as well as much overlapping coverage as geometry permitted between the Goldstone and Canberra sites. In addition to periods of the normal configuration with the DS1 HGA pointed at the earth, numerous portions of the sequence involved deliberate offpoint of the axes to accomplish navigational and science data taking by the on-board camera and other instruments.

Some of these pointing activities, within a few hours of closest approach, were to be governed by on-board software by the autonomous navigation (autonav) system, one of the DS1 technologies being validated. Turn magnitudes and start/stop times could only be estimated on the ground. From these estimates, telecom analysis generated spreadsheets of predicted signal levels and configuration change times, for use by the ACE in directing the stations to configure the receivers for the downlink and to control the uplink transmitter frequency profiles. Integral to this process was a set of signal level predicts to be included in the spreadsheet timeline.

Because the DS1 spacecraft is much more autonomous than previous ones flown by JPL flight teams, its attitude was not always known, until quite late. This required an ability to create telecom predicts on a very fast turn-around basis, as well as detailed spreadsheet sequences of events (SOE's) for up to 4 DSN stations simultaneously. Using the input GUI, it was possible to set up, run, validate, and print predicts for ACE use in 5 minutes. Validation was accomplished by review of the configuration log. The log replicates the significant GUI inputs and is automatically placed at the top of the predict tabulation.

Telecom developed predicts for contingencies, such as the possibility of a particular autonav turn not being executed,

or the spacecraft entering safing. Given the availability of two trained telecom analysts, plus support by the telecom hardware developers, and using the spreadsheet timeline, telecom recommended staffing for the more critical activities, especially those involving turns and use of the low gain antennas. Telecom staffing was required for portions of 2 shifts per day for several days, and at specific times around the clock the day of the flyby.

Detection of Abnormal Carrier Power and Recovery from Safing

Early on encounter day, about 12 hours before closest approach, the telecom analyst and the ACE were the only members of the flight team in the MSA. Monitoring the downlink at the end of an autonomous navigation ("autonav") sequence, the telecom analyst found the carrier signal level being reported by the tracking station at Canberra changed by several dB from that expected. However, the new level was within 1 dB of what telecom expected if the spacecraft had stopped the autonav activity and had gone to safemode. For telecom, safemode means the spacecraft +X axis is pointed to the sun for maximum power from the solar arrays, with the X-axis low gain antenna selected for maximum signal return to earth at this attitude. Within a few minutes, telecom recommended to the ACE that the station search for the safemode telemetry rate (20 symbols per second), using a narrower carrier loop bandwidth. The station found the subcarrier, then the symbol rate, which confirmed entry into safing. Within 15 minutes (at 5:30 am), telecom and the ACE had notified the mission director, system engineer, and fault protection engineer of the safing event.

Over the next several hours, some of the flight team generated a recovery sequence for approval. In parallel, other members tested the on-board sequence that had been executing in the test bed, and found a very probable cause for the occurrence. The test bed and analysis results gave the project confidence to approve the recovery sequence and to continue with the remainder of the on-board encounter sequence. As part of the recovery process, the telecom analyst in the MSA assessed the downlink carrier level as a function of time and was able to confidently state when the spacecraft was pointed at the sun, and subsequently to the earth, all without any telemetry data yet in lock. The end-to-end detection, analysis, testing, and recovery sequencing took 6 hours, beating the best-case expectation by an hour. The encounter sequence resumed about 6 hours before closest approach. This was 10 minutes before it would have been too late to resume, which would have caused consequent loss of the encounter science data. The safing recovery proved the value of a well experienced though small flight team, the extensive encounter rehearsal, the routine use of the test bed, the solid modeling of telecom link performance, and the "just in time" availability of accurate and prediction capability.

6. LESSONS LEARNED

Let us preface these lessons learned by saying that the DS1 mission has been a tremendous success. All 12 new technologies were extensively validated, demonstrating that they can be used on future Deep Space missions. Yet, in looking back at the feverish pace of testing, development and flight operations of the last two years, we asked ourselves, "What have we learned?" and "What could be done better?" These are statements expressing our opinion based on our experience, and they do not constitute a JPL policy or commitment.

In this context, many of the specifics below suggest better process design. Some of these telecom lessons-learned are being applied to make DS1 telecom analysis more efficient. We also hope these experiences and suggestions will result in TMOD being able to provide less expensive telecom analysis service to projects in the future.

Planning the Types and Extent of Analysis

We found DS1 telecom analysis often takes longer to do than planned and budgeted. Experience over several missions is that the amount of time telecom analysis requires is roughly proportional to the amount of time the spacecraft is being tracked. When the product of an analysis is not well defined, the analyst or customer thinks of related questions to be answered or the customer levies new requirements. Sometimes the analyst needs to create data initially believed already available. Computer processes may not run smoothly, and valuable analyst time goes into discovering that input data had not been recorded, or a server is down. It is an art to remember to allow enough time to complete a task, accounting for delays of these types.

Flight Team and Project Co-location

Having the flight team members co-located proved to be beneficial overall since points brought out in face-to-face discussion sometimes would not have surfaced through e-mail, memos, or phone calls. The turnaround time in the iterative sequence generation/review process was greatly shortened. However, in terms of analyst efficiency, there is a downside to co-location. Co-location makes it easier for one person to interrupt another with "got just a minute?" Every analyst needed to learn how to prioritize tasks and minimize interruptions from competing tasks while working the highest priority ones.

Telecom Analysis Budgeted Staffing Level

It is difficult to estimate the level of effort required to support a deep space mission operating with many "firsts": a dozen new technologies, a shorter development cycle, a smaller flight team, and an evolving TMOD service architecture. DS1 budgeted and contracted with TMOD to receive the services of one senior level telecom analyst. This analyst joined the project about one year before the planned launch. The DS1 project also intended to augment this analyst with members of the telecom systems and hardware design during the high activity initial technology validation period of 40 days. Because unexpected problems during technology validation stretched out that period and also required more real-time command and short turnaround sequences, the actual telecom staffing level averaged about two people. This could possibly have been reduced to 1.5 if the software tools used by telecom had been fully in place and mature.

It became obvious that being able to draw on a pool of three or four people was the only way to cover the "round-the-clock" staffing requirements for the first two weeks after launch. Also, having two or three individuals trained in DS1 flight operations and telecom software was essential to continue telecom support through vacation periods, illness, and critical demands on analyst time from other projects they supported.

Telecom Analysis Staffing Mix

The DS1 spacecraft safing events and restoration to operation have proved the need for a knowledgeable, experienced, and well trained analyst, but not to be "just a data watcher". The analyst may during one shift need to interpret health and safety data, do a performance trade study, review a command sequences, and give highly reliable and timely link performance predictions. In addition to the taking care of the spacecraft, this analyst adds value in understanding the needs of the DSN and how a station operates. On the other hand, it also became evident that some DS1 telecom analysis operations, especially those involved in running the software, became routine but still required about one hour of analyst time per station pass. This kind of activity could be performed by less experienced people, though interpretation of the products would continue to require the senior analysts. Looking more forward, these repetitive software tasks could be made more automated, given the time and budget to do so. An efficient and economical telecom analysis service, especially one providing support to more than a single project, requires several individuals trained in the use of the tools, each with a sufficient degree of experience to handle the tasks that the project has specified.

Need for Sequence Standardization

Improved efficiency and greater reliability result from use of tested blocks of commands that perform higher level functions – but only for repeated use. Telecom no longer has to review 90% of the telecom commands that appear individually in a DS1 sequence because these commands are the expansion of activity types and utilities.

In hindsight, it may not have been worth developing activity types for the telecom technology validation tests. In complexity, each test required 10-50 commands. The activity types, however, are intended to be reusable, but each test was only performed once. Because almost all commands were for telecom subsystem control, a customized sequence, with careful telecom review, might have required fewer workhours overall.

In the asteroid encounter sequence, telecom commands appeared in many "nested levels of subsequences. These sequences were generated independently by several engineers, and their files were not all in one place. Consequently, the telecom analyst spent much time hunting down the correct sequences and hand-merging them, because the merged product, automatically generated by the sequence team, was not correct yet. The merged products for the less complex and subsystem-interactive sequences that followed Braille encounter have generally been correct with every iteration. The cost to the telecom analyst of not having a correct encounter merged product was a series of numbingly painstaking and late manual sequence reviews. Recognizing that encounter sequences are always complex and unique, the team plans to centralize the sequence development some and constrain the types of subsequences that telecom (and other individual subsystem) commands can be placed in. The two extended mission encounters provide another chance to accomplish this.

Tradeoffs Between "Make Play" and "Make Better" (Sequence Optimization)

The necessary complexity and interaction of spacecraft activities made some sequences difficult to integrate and review. The complex sequences had many iterations, and some valuable analyst time was used up re-reviewing unchanged telecom commands in intermediate sequences. Any sequence almost always required at least four iterations, and the more complex ones twice that. The sequence integration engineers became good at localizing the effects of the changes, relieving telecom of a full review each time. Limiting the number of iterations to the minimum to "make play" and automating the sequence review process is needed to operate an extended mission with a reduced staff. The DS1 process to generate, review, test, and approve a sequence worked, but at a high cost in workload. The telecom review process was largely manual, with some simple software checks involving character string

searches and compares. When the sequence process and its products becomes more standardized from project to project, telecom analysis should develop more automated tools for sequence review.

Need for an "As Flown" Sequence

DS1 chose not to pay for the creation of an "as flown" listing of commands. From the experience of other projects, maintaining an accurate and complete list of command actually executed is very labor intensive. Commands need to be merged from the approved sequences, the approved "ad hoc" real time commands transmitted by the ACE, and the commands resulting from unplanned events such as safing and the resulting execution of on-board fault protection scripts and subsequent ground-transmitted recovery sequences and commands. More complexity results from the real time commands being able to activate, deactivate, and delete sequences of commands stored on board.

It has been labor intensive for telecom to respond to questions about what the telecom mode was at arbitrary times in the past. The questions are simple, for example, how many times has the X-band exciter been cycled off/on since launch? While such mode data can be queried over short periods of time, for long intervals it takes intelligent manual browsing of the planned sequences, the telecom "book", and the ACE log to answer the question. DS1 is investigating, for the extended mission, the amount of adaptation required to make use of "state tracking" software developed for another project.

Drawback of Simultaneous Telecom Model/Tool Development and Use

The work that telecom analysts do has become more software-intensive in part because spacecraft and station operations have become more dependent on software. On the spacecraft, this shows up in the form of a greater variety of commands and with more on-board functions controlled by the flight software. The SDST receives and outputs digital data on the spacecraft data. At the station, the small operating staff is dependent on automated functions that were previously manually controlled. Software helped DS1 telecom analysis make inputs to sequencing and review the completed sequence products. The SPW would allow DS1 telecom analysis to provide service packages directly to a more automated station control system being developed by TMOD.

DS1 was the first project to use the SPW and the first project to use the UTP to generate a DRCF. TFP had previously been used on one other project, Cassini, but during the DS1 mission, very substantial changes in the TFP architecture and "common" (station) telecom models were

being implemented. Also, priorities in the software development organization meant the comparison tools (TelRet/DCP) were not adapted for DS1 until several months after launch. The result is that DS1 telecom analysis had a very raw set of tools in place at launch. The telecom analysts had to learn the tools, use the tools, make updates of the TFP models, and verify upgrades of the tools all simultaneously. Many hours were consumed by these concurrent engineering activities that should more properly be considered development than operations.

Drawback of Simultaneous Operations Procedure Development and Use

DS1 attempted to use lessons learned by other recent flight teams, in particular Mars Pathfinder and Cassini, in doing the process engineering that led to specific procedures being required. However, there were enough differences that the formally approved procedures were very late relative to the functions being performed. One suggestion: a much better definition of roles: who does what, on what team. Within telecom we have a good idea of what is needed to predict and verify link performance, even though the depth of analysis required was at times a matter of discussion. It was less clear what products or review or support other disciplines need from Telecom. More iterations and more rework are the result of imprecise questions, often under great time pressure. At the beginning of the extended mission, the sequence process issues are being raised anew as every discipline is being downsized.

Heavy Reliance on a Capability that Never Arrived

DS1 agreed to the use of Service Packages in contrast to some other means of making telecom configuration inputs to the sequence process. This is because TMOD was restructuring the entire station configuration control process from the one known as Network Support Subsystem (NSS) to one called Network Planning and Preparation (NPP). NSS used a time-ordered DSN Keyword File (DKF) as the project statement of spacecraft telecom configuration and the resulting station requirements for a pass. NPP was to use the Service Package as a hierarchically organized listing of spacecraft information and requested "services" for a pass. Originally a functional NPP was planned to be operational before DS1 launch. Implementation difficulties delayed the NPP to three months after launch, and TMOD and the project agreed to an interim DKF backup to the DSN, while also requiring service packages on the project side. Continuing difficulties with NPP resulted in the DKF being used throughout the entire primary mission, and eventual NPP cancellation means DKF will be used for the extended mission as well.

Maintaining the dual DKF/SP process through most of the prime mission increased the workload on telecom analysis

well above the originally budgeted amount. On past missions, DKF's were automatically generated from the project SOE and did not require individual review. On DS1, there was no requirement for a project SOE, so the DKF was improvised from other software shortly before launch. This DKF did need review and hand-editing, and this burden was placed on telecom analysts. By the beginning of the extended mission, DKF generation had become reliable enough that hand-edits became the exception.

Preparation of service package inputs and checking outputs for UTP and NPP implementation absorbed telecom analysis time and resources but did not contribute to the success of the DS1 mission. The SP process on DS1 was intended as a precursor for other projects and an eventual cost-saver. Without NPP and with a planned requirement for DKF's, the extended mission offers the possibility to streamline the process for this project alone, and to make DS1 telecom analysis more efficient.

Problems with Changing Assumptions in Sequence Design

Something similar to the Flight Rules but at a higher level is needed to provide guidelines for telecom configurations from sequence to sequence. The several individuals who were sequence integration engineers and mission planners were subject to varying pressures from competing uses of the telecom links. For example, when link margin was low, some sequences were designed with downlink carrier only (no telemetry modulation), others with the 10 bps telemetry. The two configurations require different station configuration codes (which specify which equipment is assigned to a pass) and different pre-calibration times. Configuration codes and activity times are formalized in an input to SPW called the SAF (station allocation file). Changes mean the project needs to have the DSN scheduling service redeliver the SAF and to have telecom analysis regenerate the service package. The analyst reviewing sequences had to learn the constraints by asking different individuals, rather than learning one set of rules. More sequence standardization and documentation of the guidelines in the extended mission should reduce the amount of mis-communication among members of the flight team and the resulting rework.

Improve Software Ease of Use

In the rush to deliver workable, and correct software tools for DS1, there was little time to make the software more "user-friendly". As a result, it is easy to misuse it, for example by specifying an incorrect input parameter. Necessary steps to operate software not used frequently may be forgotten. We learned by using the DS1 telecom software that an analyst has the least "tool trouble" with a small tool-set in which every tool is used often. Operational software should not require many steps, complex command file

editing, going back and forth between typed-in commands and GUIs, etc. We found that memory aids (cheat-sheets) help reduce the effect of such factors.

Software use should be easy and intuitive for individuals who are under time pressure to produce a correct output and move on to another task. The SP Writer and TFP are easy to use in these regards. The UTP/DRCF and TelRet/DCP are exacting and/or time-consuming to use. The telecom analysis service of the future must refine and standardize the tool set for ease of use in efficiently providing the required service to the project.

Additional goals would include the ability to run on various platforms, have backups, and not be so dependent on services (network-accessed file storage, license managers, etc.) that may be unavailable at critical times.

The Value of Self-Documenting Software Outputs

The SP Writer produces a "log" of the GUI settings as a "comment" at the top of the file. A link "model" has been written to produce a similar log at the top of TFP tabular predicts. These outputs have proved immensely useful in telecom analyst product review, by reducing the time it takes to establish which software version produced a specific product and to verify the telecom link configuration.

Efficiency of Telecom Software Processes All on One Computer Platform

DS1, like most current projects, has some software operating behind a TMOD firewall, and other software outside the firewall. The link performance comparison process requires successive runs of several programs on different machines. These include:

- making a TFP run on a Unix workstation outside the firewall to create the prediction

- reformatting of the predict file using Excel on a PC,

- querying the spacecraft and monitor data using TelRet inside the firewall (which meant that the analyst had to physically go to a specific building), and moving the query file through the firewall, and

- merging the predict and query file in a DCP run on a workstation outside the firewall.

The present set up is very inefficient. Requiring an analyst to move files across the firewall and in some cases to physically sit in front of computers in different locations added a lot more time to the process. In the future, a better-integrated and more automated set of software tools could

lighten the workload of an analyst, perhaps making it possible to support several missions concurrently.

Software System Reliability

Much of the telecom software (TFP, DCP, and SP Writer) resides in a group account on the JPL institutional "AFS" (Andrew File System). While AFS is quite reliable, it is not perfectly robust so telecom software has not been 100% available. In critical times, having the software on a separate machine, not dependent on AFS, has reduced the problem to a matter of manageable inconvenience (to operate in a different building and to regenerate any immediately needed output that had been stored on AFS).

A functionally similar problem is that the telecom programs all require a Matlab license. Most Matlab licenses are disbursed from a central JPL "license server"; backup requires a machine with its own copy of Matlab.

Integration of Software Tools

With a spacecraft like DS1, more capable of autonomous attitude decisions, telecom analysis will come to rely more on quick turn-around ("just-in-time") prediction and performance comparison. In this, TFP was a huge step forward from previous batch-mode operational tools. However, more needs to be done to integrate all the tools, especially for performance comparison, long-term prediction and trend analysis.

Need for Integration of DRCF Output into Sequencing Process

A future automation objective is to link the DRCF to the sequence generation software to eliminate the step of manually looking up in the book and entering the bit rate that goes with a particular configuration at a particular time.

Need to Provide Station Monitor Data Access Back to Launch

Presently, monitor data is stored for only one month. We recommend storing the monitor data, or at least a filtered version of it, for the life of the project to improve access to data and synthesis of new information over long spans of time. Monitor data could be filtered in regard to the number of channels of interest to telecom (under 20) and to the number of sample points (for example, 1 average per minute, when the data is well behaved).

7. CONCLUSION

DS1 has been judged as a successful mission in that 100% of the technology validation requirements have been achieved. The primary mission, which focussed on technology validation and formally concluded a few weeks after the asteroid Braille encounter, was flown with a flight team of slightly more than 40 individuals, which averaged 2 telecom analysts. NASA has approved an extended mission, with the emphasis on science data gathering at encounters of the comets Wilson-Harrington in January 2001 and Borrelly in September 2001. Beginning in FY2000, this extended mission is planned be flown with a flight team of about 20 people, including telecom analysis at 0.5 level. The half-time telecom analyst, using the process and tools as evolved through the prime mission and described in this paper, will be able to meet the project's needs.

The telecom development and in-flight telecom analysis for DS1 has been intense. The development schedule was tight, and several new technologies were not fully developed and successfully assembled until shortly before launch. Right after launch, for nearly two months, intensive technology validation was supported by a small team. Excellent analysts, excellent tools and the dedication of an entire team made the mission a success. But we believe better planning of project and TMOD requirements, a better definition of the roles of flight team members as well as more complete integration of computer tools, will allow us to provide an excellent service with a lower cost.

ACKNOWLEDGEMENTS

The authors would like to thank the DS1 flight team for its dedication and high spirit; the DS1 Mission Manager and Project Manager for balancing the engineering, science, schedule and funding constraints so successfully; TMOD for its excellent support to DS1 routinely and during safing; and the telecom software development team for our tools.

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December 1999, Jet Propulsion Laboratory, Pasadena,
February 15, 2000

BIOGRAPHIES

Dr. Kar-Ming Cheung is a Technical Group Supervisor in the Communications Systems Research Section (331) at JPL. His group provides telecom analysis support for JPL missions, and develops the operational telecom analysis and predict generation tools for current and future JPL missions and the DSN. He received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He was the Manager of the Network Signal Processing Work Area of NASA's Deep Space Network (DSN) Technology Program. He has authored or co-authored 6 journal papers and over 20 conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and link analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.

Andre Makovsky is a telecommunications analyst at the Jet Propulsion Laboratory. Since joining JPL in 1986, he helped design and test subsystems and analyzed communications performance for the Galileo, Cassini, and Deep Space 1 missions. He has also performed trade studies for many future missions, in particular to Mars and Pluto. He received his BS and MS in Electrical Engineering from Rensselaer Polytechnic Institute in 1984 and 1985 respectively.

Jim Taylor has been a telecom systems engineer and a flight team telecom analyst at the Jet Propulsion Laboratory since 1970. He has been involved in pre-launch telecom link design and flight operations for the Mars-Mariner, Viking Orbiter, Galileo Orbiter, and Deep Space 1 missions. He received his BS and MS degrees from Stanford University in 1961 and 1972 respectively.


```

Output SP File: DS1_34_99304_V00B_090899181714.spf

Input Allocation File: /afs/jpl/group/ds1_tele/allocation/DS1_99249_99362.saf
Track: 1999-304 23:00 to 01:05, dss34, Pass #0374, V00B, TP/XHGT/2WAY.ADD

SP Writer GUI inputs
  Services Requested: Telemetry Command Ranging
  S/C Antenna: HGA
  Encoding : RS/CE K=15 1/R=6
  Down Link RF Band : X only
  Telemetry Data Rate : 1050.000 bps.
  Tlm Mod Index (X) : 65.800 deg.
  Ranging Mod Index : 17.500 deg.
  Ranging Suppression: 3.000 dB.
  Command Data Rate : 250.000 bps.
  Command Suppression: 3.500 dB.

Special Services: IPS not selected.

Produced by DS1 SPWriter V1.2 07/15/1999 on 1999/09/08 at 18:17:14.
GUICODE,1,1,2,1,1,11,7,2,2,1,1,1,1,0
***** */
BEGIN_GROUP = DS1_34_0374_V00B_090899181714;

mission = DS1;
sc_number = 30;
equipment_set = {DSS34, XHEMT, inherited};
start_time = 1999-304T23:00:00Z;
stop_time = 1999-305T01:05:00Z;

BEGIN_GROUP = DS1_34_0374_V00B_X_090899181714;

BEGIN_OBJECT = DS1_34_0374_V00B_X_DOPP_090899181714;
  dichroic_plate_mode = X_only;
  doppler_mode = '2-WAY';
  downlink_band = X;
  downlink_frequency = 8421.764276 <MHz>;
  dsn_receive_polarization = RCP;
  dsn_transmitter_power = 3565 <watt>;
  dsn_transmit_polarization = RCP;
  feed_selection = X;
  microwave_path = 'DIPLEX';
  sc_coherency = ENABLE;
  sc_receiving_antenna_type = HGA;
  sc_transmitter_power = 12.5 <watt>;
  sc_transmitting_antenna_type = HGA;
  sc_receive_polarization = RCP;
  sc_transmit_polarization = RCP;
  service = doppler;
  table = (NPP, mst, 'DS1_XX_doppler.mst');
  transmitting_dss = 'DSS34';
END_OBJECT = DS1_34_0374_V00B_X_DOPP_090899181714;

BEGIN_OBJECT = DS1_34_0374_V00B_X_BITS_090899181714;
  depends_on = 'DS1_34_0374_V00B_X_DOPP_090899181714';
  inner_code_rate_divisor = 6;
  inner_constraint_length = 15;
  service = bit_stream;
  table = (NPP, mst, 'DS1_bit_stream.mst');
  tlm_data_rate = 1050 <bps>;
  tlm_modulation_index = 65.80 <deg>;
  tlm_subcarrier_frequency = 25000.700 <Hz>;
  tlm_symbol_rate = 6300 <sps>;
END_OBJECT = DS1_34_0374_V00B_X_BITS_090899181714;

BEGIN_OBJECT = DS1_34_0374_V00B_X_ALLF_090899181714;
  depends_on = 'DS1_34_0374_V00B_X_BITS_090899181714';
  service = all_frame;
  table = (NPP, mst, 'DS1_all_frame.mst');
END_OBJECT = DS1_34_0374_V00B_X_ALLF_090899181714;

BEGIN_OBJECT = DS1_34_0374_V00B_X_CMDR_090899181714;
  depends_on = 'DS1_34_0374_V00B_X_DOPP_090899181714';
  cmd_data_rate = 250.0000 <bps>;
  cmd_suppression = 3.5 <dB>;
  service = cmd_radiation;
  table = (NPP, mst, 'DS1_cmd_radiation.mst');
END_OBJECT = DS1_34_0374_V00B_X_CMDR_090899181714;

BEGIN_OBJECT = DS1_34_0374_V00B_X_RNG_090899181714;
  depends_on = 'DS1_34_0374_V00B_X_DOPP_090899181714';
  downlink_rng_modulation_index = 17.50 <deg>;
  uplink_ranging_suppression = 3.00 <dB>;
  service = ranging;
  table = (NPP, mst, 'DS1_XX_ranging.mst');
END_OBJECT = DS1_34_0374_V00B_X_RNG_090899181714;

END_GROUP = DS1_34_0374_V00B_X_090899181714;

END_GROUP = DS1_34_0374_V00B_090899181714;

```

Figure 2: Sample Service Package

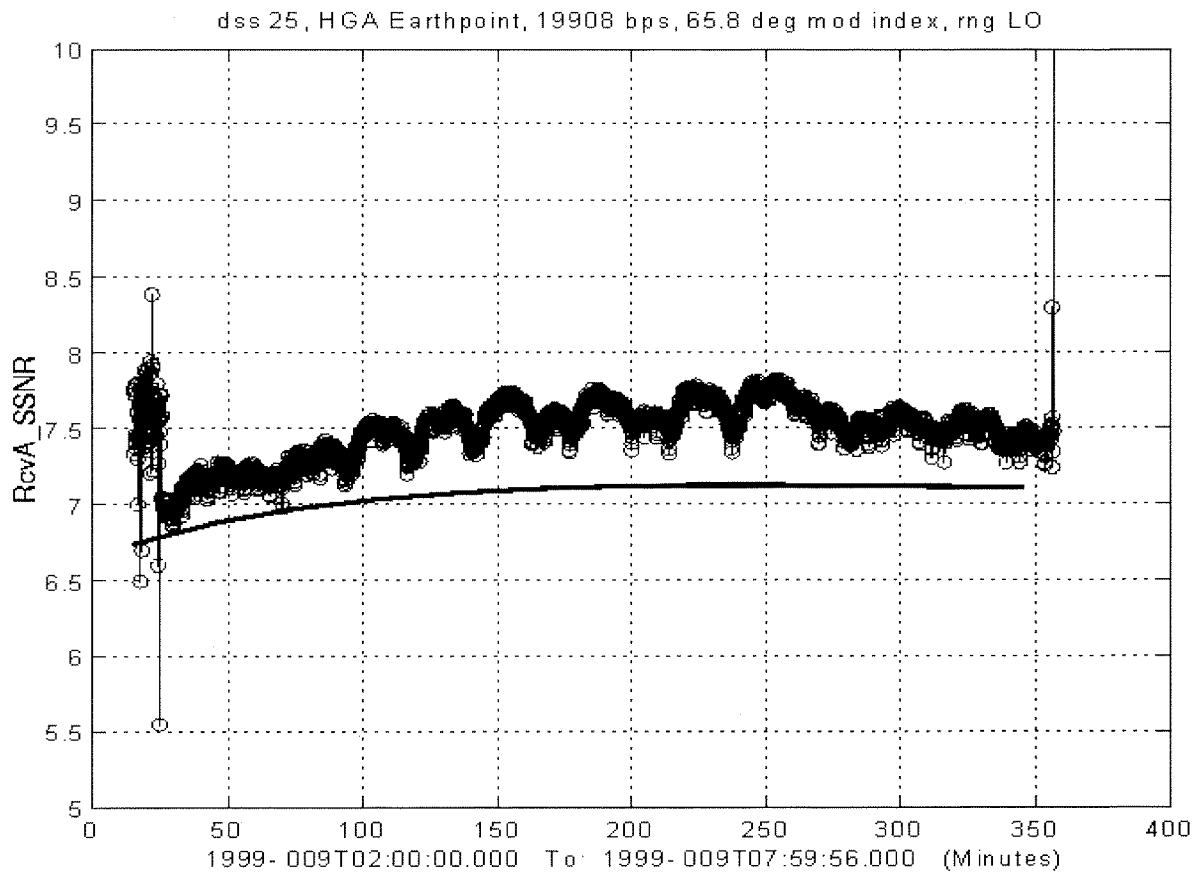


Figure 3: Sample TelRet/TFP/DCP Output

Note: the actuals data was queried via TelRet, the predicted signal level was produced by TFP (it is the smooth plot), and DCP synchronizes both data streams and plots them. The residual appears graphically as the difference between the actual level and the predicted signal level.

Trajectory and DSN File Interfaces on DS1

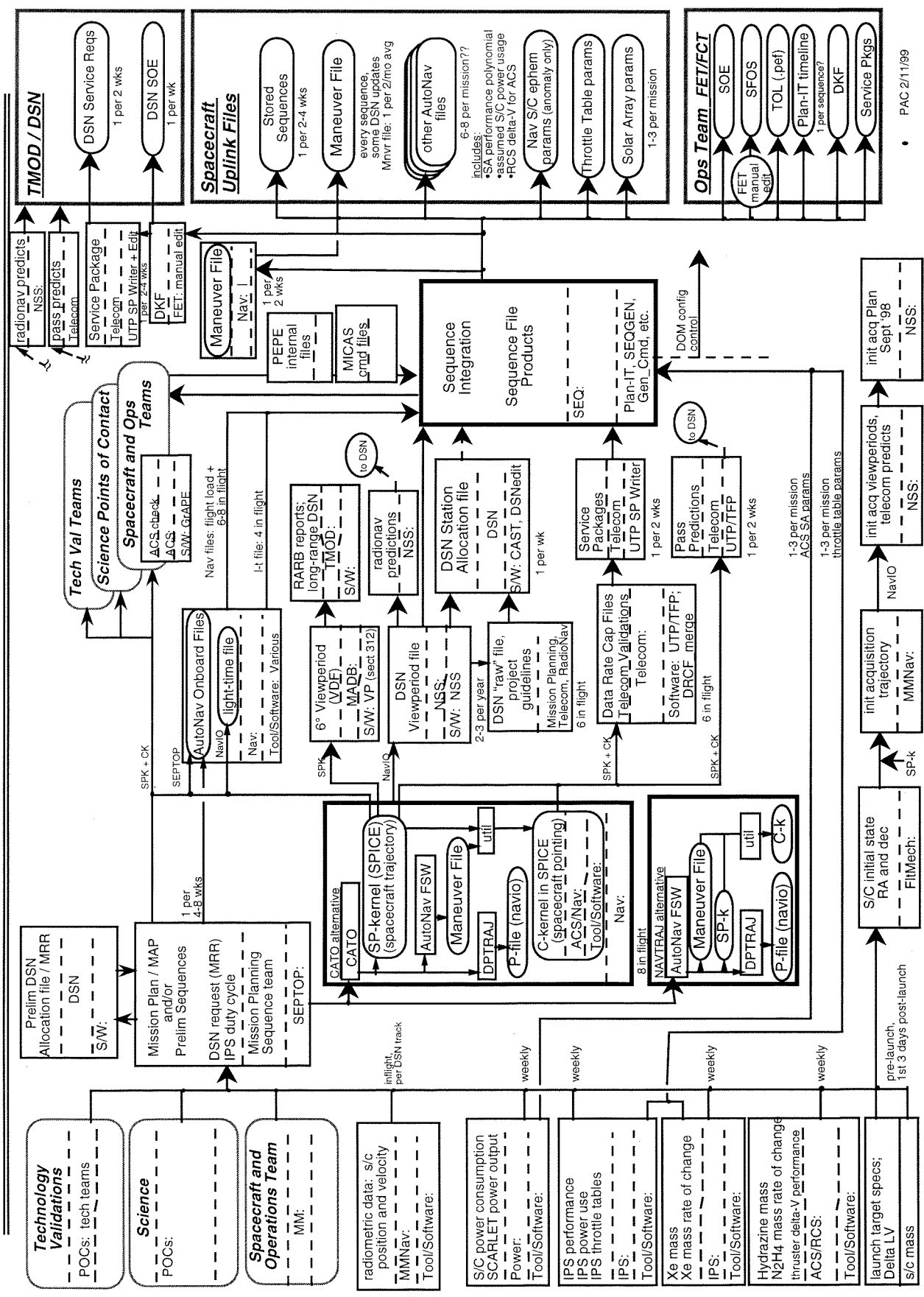


Figure 4: Fileflow Diagram